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Fusion Engineering and Design 61–62 (2002) 245–250

Fusion Engineering and Design

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FLIRE—flowing liquid surface retention experiment, design and testing

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Abstract

The flowing liquid surface retention experiment (FLIRE) has been designed to provide fundamental data on the retention and pumping of He, H and other species in flowing liquid surfaces. The FLIRE concept uses an ion source with current densities near 0.5 mA/cm^2 and a working distance of 30–40 mm. The ion source injects 300–5000 eV ions into a flowing stream of liquid lithium at nearly normal incidence. FLIRE is a dual chamber unit. The liquid lithium flows into one vacuum chamber isolating it from a bottom vacuum chamber. Two residual gas analyzers with a quadrupole mass spectrometer, monitor the partial pressure of the implanted species in each vacuum chamber measuring retention and diffusion coefficients. A liquid–metal (LM) injection system experiment has been carried out to verify the capability of transporting liquid lithium. Results show that liquid metal velocities of the order of 1 m/s can be achieved. Safety tests conclude that exposing 300 °C lithium to atmosphere result in benign chemical reactions. A test of the external and internal heating systems conclude that LM transfer lines can be heated to temperatures near 270 °C and ramp temperatures near 400 °C.

Keywords: Free surface flowing liquids; Particle retention; Liquid lithium; Diffusivity; Plasma-facing component

1. Introduction

One of the critical technological challenges of future fusion devices is the ability for plasma-facing components (PFCs) to withstand power densities of the order 5–10 MW/m^2, for advanced tokamak machines, and up to 50 MW/m^2 for off-normal events such as edge-localized modes or disruptions [1–3]. One alternative addressing this challenge is the use of free surface flowing liquids as PFCs. Some examples of these free surface liquids include: liquid–metals (LMs) such as liquid lithium and non-conducting fluids, such as flibe ($LiF–BeF_2$). Therefore, understanding important free surface flowing liquid–plasma interactions such as: mean flow LM velocity, He/H particle retention, particle surface segregation, turbulence effects on particle retention, and LM erosion transport is crucial to the development of ad-

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0920-3796/02/$ - see front matter
PII: S0920-3796(02)00118-7

vanced plasma-facing liquids for use in future-generation fusion machines [4].

To this end a new facility, the flowing liquid surface retention experiment (FLIRE) at the University of Illinois has been built. FLIRE is currently designed to study the interaction of energetic bombarding ions from an ion source with free surface flowing liquid lithium at moderate surface temperatures. This interaction includes such mechanisms as: impurity transport from both sputtering and evaporation, and more importantly, injected particle retention and release properties. These retention properties of flowing PFCs are critical to determine fuel recycling regimes (for the case of hydrogen isotopes) and ash removal/release rate (for the case of helium), among other relevant properties [5]. This work describes the experiment, its major components as well as present relevant data on tests of individual components of FLIRE with the use of liquid lithium.

2. Experimental design

FLIRE consists of several systems that work together to ultimately measure fundamental properties such as particle retention/release properties from free surface flowing liquids exposed to high-intensity ion beams or low-temperature plasmas. These integrated systems include a vacuum assembly, a LM injection system (LMIS), an internal ramp system, an ion beam source, and two residual gas analyzers (RGA's). Currently FLIRE uses liquid lithium as the working liquid and thus an external and internal heating system has been designed to keep lithium molten. Following is a description of each of these systems.

The major vacuum components of FLIRE are shown in a schematic in Fig. 1. The upper vacuum chamber is pumped by a 2000 L/s (N_2) magnetically-levitated turbomolecular (TMP) pump and a 1500 L/s cryogenic pump. The bottom vacuum chamber is equipped with a TMP but with a pumping speed of 300 L/s. Two vertical, cylindrical LM reservoir chambers are connected in series below the bottom vacuum chamber and are heated to temperatures near 270–300 °C. The total pumping volume of the top and bottom chambers and the upper reservoir is approximately 35 L and the vacuum system routinely reaches a base pressure in the low 10^{-9} Torr regime.

The method used for heating the ramps employs 10-mil tungsten wire shaped to deliver uniform heating placed between thin (1/16-in.) alumina plates mounted to the underside of the ramps; Fig. 2 shows a picture of the current setup. Currents of 4 A (or $\sim$7900 A/cm^2) are passed through the heater wires to deliver 270 W of energy to the ramps, which raises the ramp temperatures from room temperature to 386 and 409 °C depending on location. To allow for thermal expansion the lengths of the alumina plates have been cut in half. Fig. 2 shows the stainless steel ramps with the heaters attached to the bottom inside the upper vacuum chamber. The ramp temperature is monitored by thermocouples at two positions along the side of one of the ramps.

Instead of using the preferred flowing liquid lithium loop, a batch process was conceived to meet budgetary constraints. Lithium is initially melted in the lower reservoir under an argon atmosphere to improve thermal conductance between the externally heated chamber walls and the solid lithium foil. Liquid lithium is pumped with the use of pressurized argon from the lower reservoir chamber through heated tubing back to the sides of the top chamber and onto two heated internal ramps (Fig. 2) with flow velocities along the ramps on the order of 1 m/s; these ramps guide the open-surface flow laterally and bring the two streams of liquid together at an orifice which leads into the bottom chamber and the upper reservoir. Between the two LM reservoirs is a LM-compatible inline valve that is actuated to control LM flow into the lower reservoir for preparation of another batch run. Another LM compatible valve is used inline between the lower reservoir chamber and the LM lines leading to the upper chamber, which automatically closes once most of the liquid lithium has been removed from the lower reservoir chamber to prevent bubbling of the liquid metal. Again, thermocouples are used to monitor the temperatures throughout the system. Temperature controllers with solid-state relays and/or variable

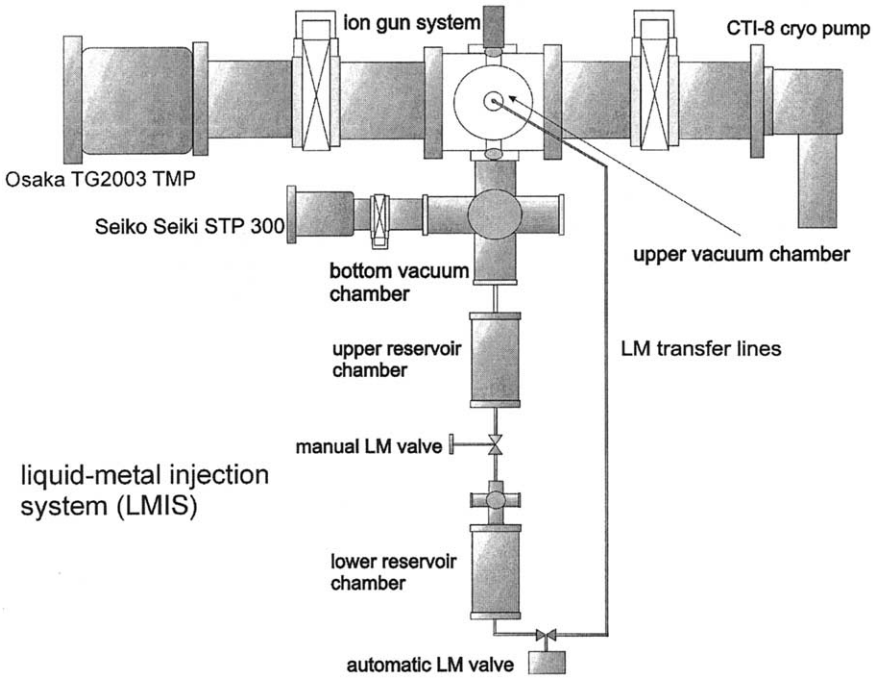

Fig. 1. FLIRE major vacuum components consist of two chambers each with a turbomolecular pump and RGA-QMS systems (not shown).

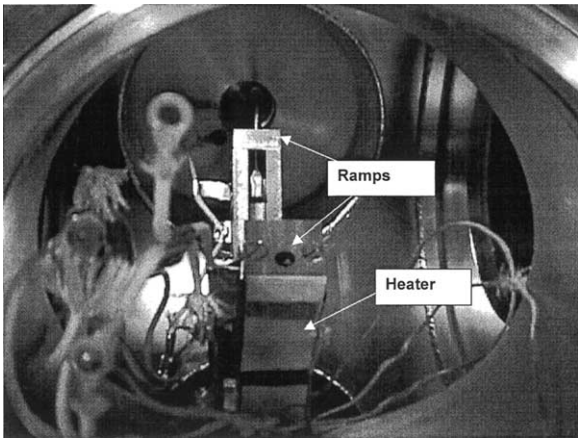

Fig. 2. Internal ramp systems with tungsten-wire/alumina heaters installed on the bottom of the ramps. The internal heating system heated the stainless steel ramps to temperatures near or above 400 °C.

transformers are used to obtain the desired temperatures (typically 250–300 °C).

In its current design, FLIRE uses an ion beam to inject helium (or other) ions at near normal

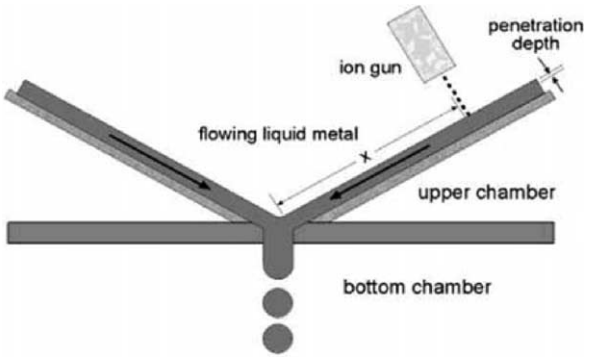

Fig. 3. Expanded view of upper and bottom chambers in the FLIRE system. The ion gun is placed about 50 mm away from the free surface liquid lithium flow.

incidence into the flowing stream of liquid lithium (Fig. 3). The ion gun system uses electron-impact ionization of gas as an ion source and can achieve current densities on the order of 0.5 mA/cm^2 with a working distance of 30–40 mm for incident energies ranging from 300–5000 eV.

3. Results and discussion

In order to assess the performance of systems important to FLIRE, a set of mock-up and preliminary experiments were designed and performed ex-situ at a reduced scale. In addition a set of safety and handling tests were performed with liquid lithium. Following is a description of all experiments and tests, and a discussion of their results.

3.1. Liquid metal injection system mock-up test

A LMIS mock-up was built and was used to test the melting and transport of liquid lithium under similar conditions in the FLIRE experiment. The small chamber used in melting the lithium sample for the LMIS test consisted of a right cylinder, 3.8 cm in diameter and 12.7 cm long. The molten lithium went through a set of tubing as depicted in Fig. 4 from the lower chamber, where it was melted, to the upper chamber. The driving force to pump the liquid lithium from the lower chamber to the upper chamber was provided by increasing argon pressure on top of the liquid. The stainless steel lines were kept at temperatures near 270 °C during the experiment. From a video of the flow, the flow velocity was estimated at 70 cm/s, which correlates to a mass flow rate of 2 g/s with the current geometries. Also, the calculated 33.5 Torr pressure difference necessary to overcome gravitational and frictional forces proved to be accurate. This mock-up experiment verified our abilities to melt and transport lithium at rates needed by the FLIRE experiment.

3.2. Safety handling procedures

In addition to the small-scale lithium flow experiment, valuable information about the interaction of lithium with the vacuum components and the environment was determined. One useful observation was that liquid lithium at 250 °C does not wet stainless steel but adheres very well to it upon cooling. Previously, it was found that exposing lithium at high temperatures (~ 400 °C) to relatively hot (30–70 °C) water led to a high likelihood of an explosive reaction [6]. In

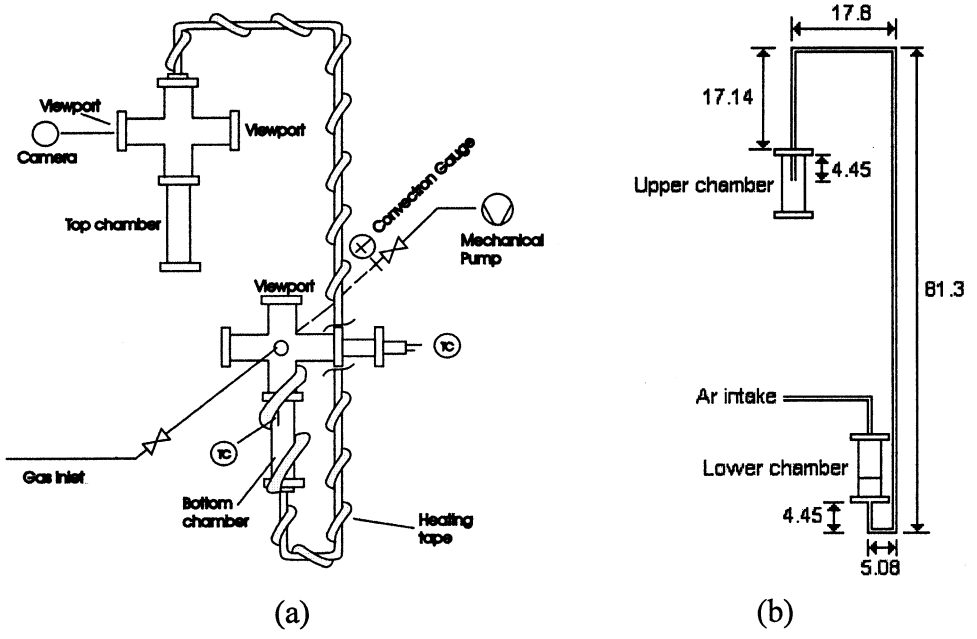

Fig. 4. (a) Experimental setup for liquid lithium injection mock-up test to verify flow velocity and argon pressure control. (b) Dimensions of experimental setup for the LM injection mock-up test. These dimensions are in centimeters.

order to evaluate our particular system, an intentional loss of vacuum accident was performed with minimal effects. Following the safety review, a procedure to clean the surfaces safely with deionized water was devised.

3.3. Internal heating systems

The objectives of these experiments were to test primary components, determine whether additional heating would be required to have the orifice at the desired temperature, and the nature of the gases evolving from the ramps. Fig. 5 shows how quickly the temperatures change using the heating systems described above. Three different power levels of 30, 120, and 270 W were applied to the ramps after the orifice flange was heated to $\sim$ 240 °C. The slopes of the temperature vs. time plot in Fig. 5 clearly show when the power level was changed at $t = 0$, 52 and 144 min, respectively. Upon each increase in power level, the temperature would approach an equilibrium temperature predictable by using one known relation between power and temperature and use of the T^4 law of radiative cooling. Also, when the power level was increased to 270 W, the partial pressures of the dominant gases changed; nitrogen started as the most abundant at 4.77×10^{-8} Torr and reached

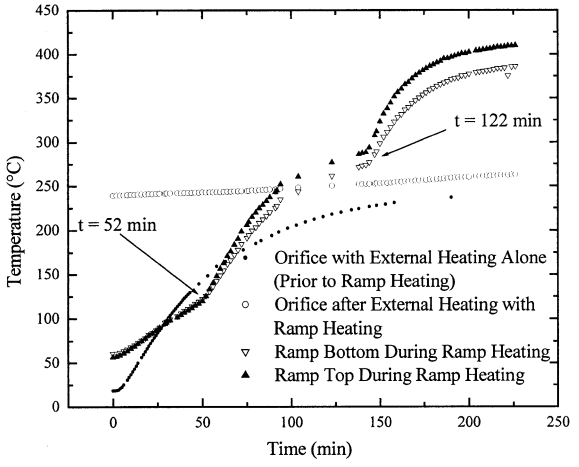

Fig. 5. This figure shows a superposition of results from two consecutive experiments with $t = 0$ designating the start time of each experiment. The size of the error bars of this plot is within the size of the data marks.

up to 1.1×10^{-7} Torr after heating. The remaining recorded gases increases slightly and all eventually reduced over time.

3.4. Ion gun system tests

A SPECS IQE 11/35 ion gun is used as the plasma source in FLIRE. The gun can deliver ions with energies up to 5 kV. Currents on the order of 5 μA at an energy of 2 kV for hydrogen and helium were measured in a 25 mm^2 square sample placed at the bottom of the ramp, located 35 mm away from the tip of the ion gun.

3.5. Measurement of diffusion coefficient

The gas retention and release properties of liquid lithium, closely related to both bulk and surface diffusion, can be obtained from the data obtained in FLIRE. The release of gas from a liquid metal, and in this case liquid lithium, involves two competing mechanisms: bulk diffusion from the implantation depth to the surface, and surface recombination. A simple model based on the diffusion-limited case (valid for those gases that don't need to recombine to be released) was used to determine a range of measurement for the diffusion coefficient, D, given the RGA sensitivity. The density profile, $n(x, t)$, obeys the diffusion equation (Fick's law) with x representing the distance along the ramp from the point at which the ion beam strikes:

$$\frac{\partial n(x,t)}{\partial t} = -D\frac{\partial^2 n(x,t)}{\partial x^2} \tag{1}$$

The Green's function corresponding to the problem of a semi-infinite domain subject to a no-flux boundary condition at $x = 0$ (no diffusion into the ramp) with parameter ξ is:

$$G(x;\xi,t) = \frac{1}{\sqrt{4\pi Dt}} \times \left\{ \exp\left[-\frac{(x-\xi)^2}{4Dt}\right] + \exp\left[-\frac{(x-\xi)^2}{4Dt}\right] \right\} \tag{2}$$

So for a given initial profile $n_0(x)$, the final solution to the diffusion equation is given by:

$$n(x,t) = \int_0^\infty n_0(\xi) G(x;\xi,t) \mathrm{d}\xi \quad (3)$$

The particles retained inside a film of thickness a as a function of time can be calculated as:

$$r(t) = \int_0^a n(x,t) \mathrm{d}x \quad (4)$$

Knowing the initial deposition profile, the total thickness of liquid metal film, the transit time from the striking point of the beam to the second chamber entrance and the pumping characteristics of the second chamber, the diffusion coefficient D can be calculated, since r can be obtained from the P vs t measurements in the second chamber of FLIRE. A more complete model that includes surface recombination, which uses a realistic initial profile and removes the limitation of the semi-infinite domain, is currently under development. Data on hydrogen retention and recombination in static liquid lithium can also prove to be helpful [7,8]. The simple model presented here predicts that diffusion coefficients between 10^{-6} and 10^{-3} cm^2/s can be measured.

4. Conclusions

A description of the main systems in FLIRE have been described and discussed. In addition, a set of mock-up and preliminary experiments has been completed in order to assess the performance of individual components. A LMIS is used to melt, transport and collect about 1 kg of 99.99% lithium. An ion gun source is used to provide helium or hydrogen bombardment at near normal incidence and relatively low bombarding energies. A RGA-QMS system is used in both the upper and lower vacuum chambers to monitor implanted species and measure, among other parameters, diffusion coefficients in the free surface flowing liquid lithium.

Acknowledgements

We would like to acknowledge the STTR-DOE subcontract grant DE-FG02-01ER86134 from NPL Associates Inc., and also G.H. Miley who is President of NPL Associates Inc. In addition the ALPS-DOE grant DE-FG02-99ER54515 is acknowledged. We would also like to thank Dr Jeffrey N. Brooks, Dr Ahmed Hassanein and Dr Mike Ulrickson for helpful discussions.

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